Lunar Applications in Reconfigurable Computing

Kevin Somervill
NASA Langley Research Center
Hampton, VA

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Abstract

NASA's Constellation Program is developing a lunar surface outpost in which reconfigurable computing will play a significant role. Reconfigurable systems provide a number of benefits over conventional software-based implementations including performance and power efficiency, while the use of standardized reconfigurable hardware provides opportunities to reduce logistical overhead. The current vision for the lunar surface architecture includes habitation, mobility, and communications systems, each of which greatly benefit from reconfigurable hardware in applications including video processing, natural feature recognition, data formatting, IP offload processing, and embedded control systems. In deploying reprogrammable hardware, considerations similar to those of software systems must be managed. There needs to be a mechanism for discovery enabling applications to locate and utilize the available resources. Also, application interfaces are needed to provide for both configuring the resources as well as transferring data between the application and the reconfigurable hardware. Each of these topics are explored in the context of deploying reconfigurable resources as an integral aspect of the lunar exploration architecture.

Contents

1 Introduction

The National Aeronautics and Space Administration (NASA) is currently developing an architecture of vehicles, communication systems, and infrastructure as part of the Constellation Program (CxP) objective to return to the moon and establish long-term habitation there. For the last several years, considerable effort has been invested in cultivating an understanding of what it takes to establish an outpost that will serve as a proving ground for subsequent manned space exploration including outpost settlement on Mars. The development of the outpost faces a number of challenges including a long period of development and piece-wise build-up similar to the construction of the International Space Station (ISS). The current concepts for the architecture are rich with diverse elements specifically formulated to address these challenges as well as the various environmental and technical challenges of extra-terrestrial exploration. This paper presents a general overview of the use of Reconfigurable Computing (RC) in the context of the lunar surface architecture.

1.1 Characteristics of the Outpost

There are a number of characteristics of the outpost architecture that must be addressed. The development will certainly occur over several years and very likely over the entire lifetime of the outpost which has a planned period of performance of at least a decade. Given the long term deployment, the architecture as a whole must be maintainable and sustainable, both of which must account for affordability. Also, sustainability will need to address the potential to react to changes in priority as well as opportunities from technology and experience as the development progresses. This implies a quality of *evolvability* in the architecture to enable a degree of flexibility as well as accommodate cooperative development and participation with international partners. To address these characteristics, the architecture is being developed from common, interoperable components based on open industry standards.

1.2 Benefits of Reconfigurability

RC has consistently demonstrated a number of benefits over of static, fixed-function, or general purpose hardware including performance and power as well as inherent commonality and component reuse. While general purpose processors have become established as the dominant computing resources, the fact that they are multi-purpose by nature means that they are not optimal for many compute intensive applications. Where the desired performance exceeds that of the available processor, special purpose implementation optimized uniquely for the application supplants the processor and software executive. The Programmable Logic Device (PLD) enables near Application Specific Integrated Circuit (ASIC) performance without incurring the considerable development and fabrication costs of an ASIC implementaiton. In porting the application from the sub-optimal software executive to a PLD, power is also improved due to both the optimization as well as the removal of unnecessary collateral functionality.

As alluded to above, utilizing common components is a key aspect of realizing the current vision for the architecture. Reconfigurable Computing extends this commonality to reuse of hardware for dissimilar applications which in turn caters to flexibility in functionality (evolvability). It also reduces required sparing of different elements and potentially facilitates replacement of dedicated hardware with reconfigurable hardware (maintainability). For these reasons, RC has consistently found its way into trade studies, applications, and conceptual element architectures, some of which are discussed in the follow sections.

1.3 Organization of this Report

The remainder of this report presents the use of RC in the development of the lunar surface architecture through the description of various applications and elements. The following sections are organized as follows. Several applications are presented in section 2 followed in section 3 with an overview of the systems hosting these applications. Section 4 briefly address issues of managing reconfigurable assets. Section 5 closes this report with some concluding remarks and forward work.

2 Applications

2.1 Video Processing Unit

The Video Processing Unit (VPU) is the core of the video system enhancing some functions while enabling others. The basic purpose of the VPU is the processing and management of the onboard video streams either for local use or transport to an external destination. This function includes compression, encoding, and decoding using formats such as MPEG H.264. Utilizing RC to implement this enables the additional functions of feature recognition (pattern matching), enhancement (edge detection and highlight), or fusion using multiple views (visible and non-visible spectrum) for removal of occultation or accentuation of features. Extending this functionality, the VPU can serve to route video streams to desired destinations with configured or on-demand processing enabling real-time video display at the crew interfaces.

2.2 Advanced Instruments

The potential of RC is easily appreciated when considering the enabled advances in onboard instrumentation including Natural Feature Image Recognition (NFIR) used in Autonomous Rendezvous and Docking (AR&D) and Autonomous Landing and Hazard Avoidance Technology (ALHAT) used during landing operations. Previous space flight vehicles have demonstrated orbital rendezvous and docking maneuvers including the shuttle mating with the ISS. The use of RC will be used to extend this to an autonomous operation as part of the lander-to-Orion vehicle mating where NFIR technology is employed to track the mating interface of the target vehicle. An earlier version of NFIR has been previously implemented on the SEAKR Reconfigurable Computer Card (RCC) for autonomous docking with the Hubble Space Telescope[1]. The current generation algorithm has been demonstrated with commercial Pentium™class processors and has the potential for being ported to PLD technology to increase the performance and operational efficiency as well as mitigate the environmental effects. Figure 1 depicts an augmented video display using NFIR. In this display, the camera video has been processed using NFIR with detected features highlighted in green. The detected features are compared against a 3D model of the target to estimate position and orientation of the active vehicle relative to the target and in turn generate commands for the Guidance, Navigation, and Control (GN&C) during approach and docking. The augmented display is provided to the crew for supervision during the process. Assuming the availability of the above VPU as a reconfigurable system asset, the application power is considerably reduced from that of its software equivalent without incurring a mass penalty for the functionality.

Another advanced instrument, ALHAT[2], utilizes RC resources to enable autonomous

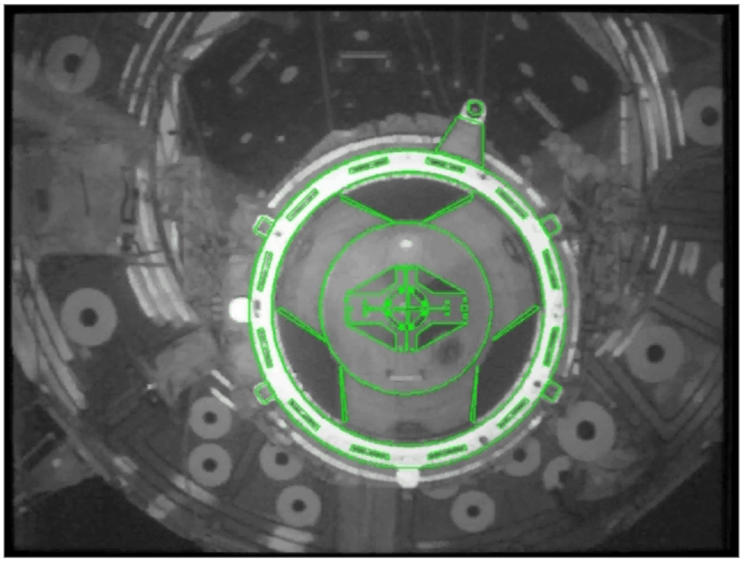
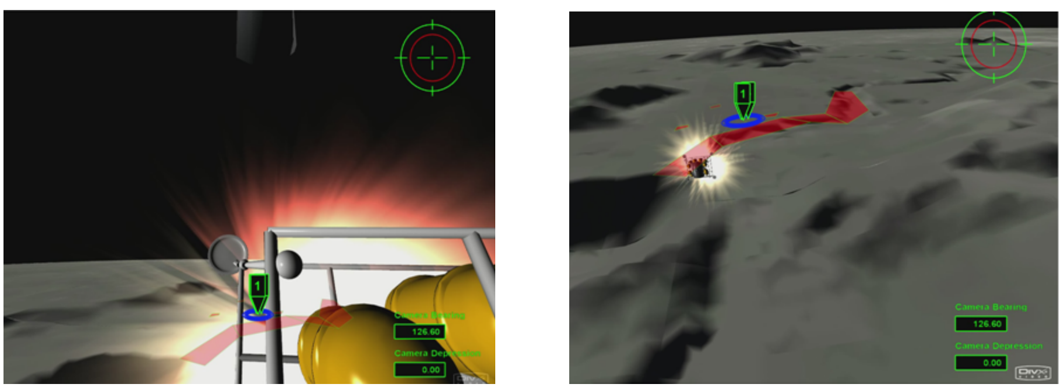


Figure 1: NFIR display with overlay



(a) Camera view of landing site approach and hazards

(b) “Wingman” view of landing site and hazards

Figure 2: Conceptual ALHAT crew displays

landing providing the capability to react, in real-time, to surface hazards at the planned landing site in spite of poor lighting conditions, significantly increasing the probability of a safe landing for both crewed and robotic missions. During landing, ALHAT will process input sensor data (visible and non-visible spectrum images) for terrain relative and hazard relative navigation. ALHAT then generates commands for the GN&C, autonomously landing crew and cargo on the lunar surface. Current efforts are evaluating candidate front-end sensors including passive optical, radiometric, and LIDAR, but regardless, the collection and processing is challenging with RC being an excellent candidate for implementing the algorithms. Additionally, ALHAT provides the potential to enhance crew productivity with “artificial surface illumination”, video augmentation, and “synthetic vision sensor fusion”[2]. Again, an onboard VPU could facilitate this image processing and sensor fusion for display to the crew interfaces or even suit Heads Up Display (HUD) for supervision of the landing process. Examples of the crew displays are shown in figures 2(a) and 2(b). In figure 2(a), ALHAT data is overlaid on landing camera video highlighting hazards in red and optimal landing sites with blue circles and numbered flags. Figure 2(b) depicts the “wingman” view of the landing approach as seen from outside the lander.

2.3 Systems Health Monitoring and Diagnostics

Considering the longevity of the outpost mission, System Health Monitoring (SHM) will play a critical role in the lunar architecture. RC will support SHM for both control and data handling. Providing control is achievable either using low-level controllers (state-machine or microcontroller embedded in the PLD) or using embedded microprocessors as available in the Virtex-4 and Virtex-5 devices[3, 4]. The health data is then collected for formatting for telemetry while the use of embedded processors simplifies engineering unit conversion if desired and enhances the potential for local control to prevent damage or maintain fault containment. The use of the RC hardware enables the trade of special purpose, custom implementions verses a more highly abstracted development and embedded processors executing software routines.

Either to evaluate system health or recover from detected faults, diagnostics will provide insight into the operational state of the various systems. In-system RC hardware can support both low level monitoring such as bus monitoring and logic analysis as well as support system debug functions. In shared bus systems, a reconfigurable bus agent could be configured to monitor and record bus traffic for the purpose of detecting protocol errors or to validate correct operation of a recently repaired system. It can also support fault injection to verify fault detection and isolation capabilities in the host system. The U.S. Department of Defense (DoD) has established an initiative to develop Synthetic Instruments (SI) for automatic test systems[5, 6]. Utilizing PLD and signal conditioning, SI can be used for in system test and evaluation. This can be implemented to varying degrees utilizing available RC resources.

2.4 Communications

In the domain of communications, RC supports similar roles as those of the VPU providing compression and formatting functions as well as potentially supporting routing functions. Also, Software Defined Radio (SDR) technology will utilize RC hardware for waveforming and encoding enabling real-time data processing[7, 8]. General purpose processors embedded in the RC hardware potentially enable a single board solution to cover all layers of the protocol stack from application interface to the baseband output[9] at the physical layer. This will greatly simplify the development of the communications infrastructure and maintenance through the use of a common module to support multiple communications protocols in different systems. Used for co-processing, RC can be used for Internet Protocol (IP) off-loading, considerably reducing the processing required for networking applications.

3 Lunar Systems

The development of the lunar outpost yields a number of elements that will benefit from the utilization of Reconfigurable Computing. A conceptual illustration shown in figure 3 demonstrates the elements of the completed outpost. Examined in the order from transportation to the lunar surface, to the habitation elements of the outpost, the following sections briefly describe the use of RC in the lander, mobility, and the habitation elements. Each of these elements contribute different capabilities to the surface architecture and yet share common subfunctions (such as displays and controls) indicating opportunites for commonality that are only complimented with RC.

3.1 Lunar Lander

The lunar lander is responsible for the safe delivery and return of crew and cargo to and from the lunar surface. It provides a number of opportunities for using RC in each of the application domains described above. Onboard video and routing of crew display video drive the performance of the network where the VPU plays a central role. Camera data for docking, landing, and crew operations will be processed and routed, by the VPU, to local crew displays, mission operations, data storage systems, and remote CxP elements. RC will be used in advanced instruments increasing the safety of critical operations through sensor data processing and fusion. Autonomous operation of docking and landing maneuvers greatly reduces the risk associated with uncrewed, robotic cargo delivery to the lunar outpost. Also, the use of RC for SHM simplifies design, increases performance, and reduces power while providing embedded controls of data acquisition systems as well as data and telemetry packet processing.

3.2 Mobility

The development of the lunar surface architecture has required mobility to accommodate various surface activities. Among the different classes of surface vehicles the Char-

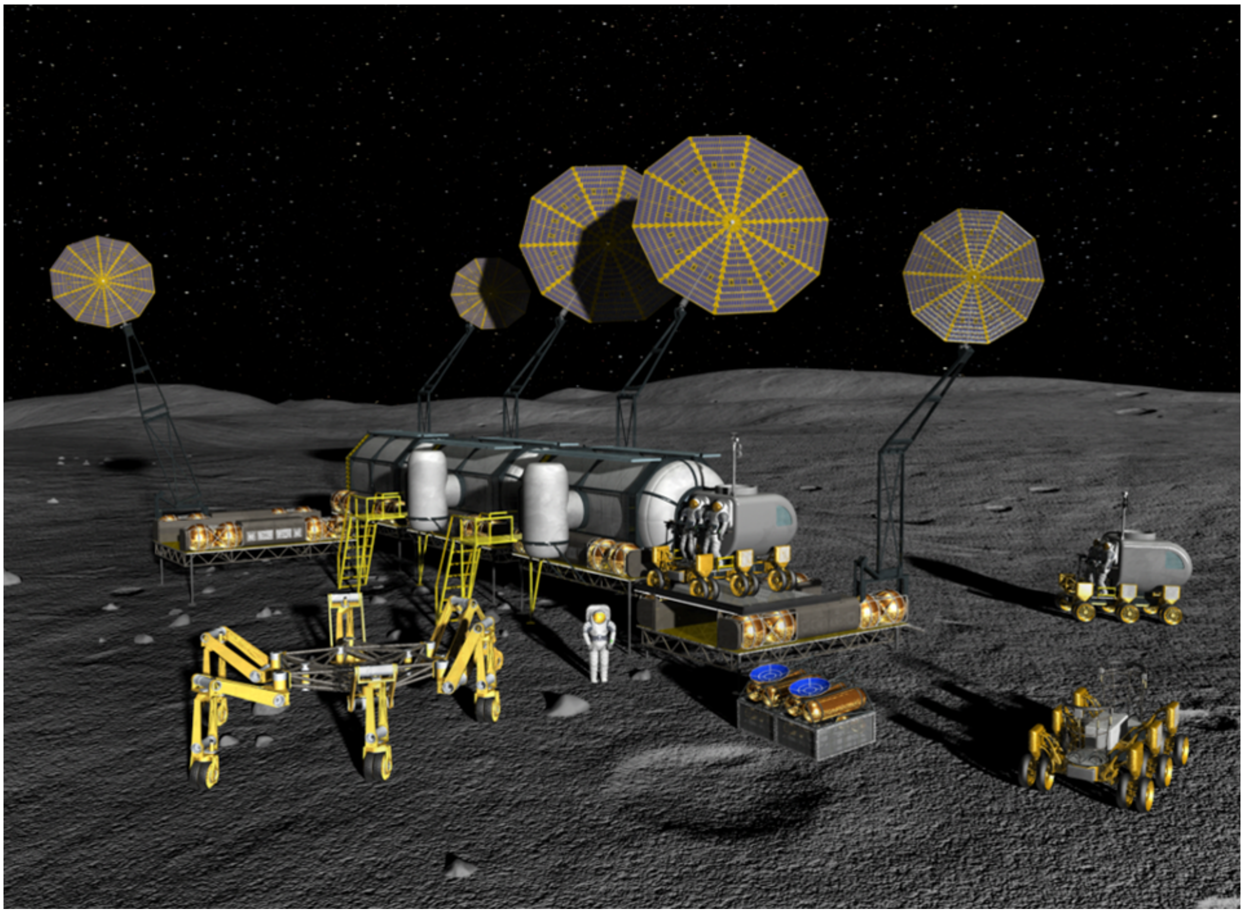


Figure 3: Conceptual outpost on the lunar surface

iot and the All Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) have established themselves as leading contenders with complimentary functionality. Both vehicles are modular systems supporting both Extra-Vehicular Activity (EVA) and cargo transport with many opportunities for use of RC. In autonomous operations, NFIR and ALHAT could be adapted to support surface activities such as surface navigation, terrain mapping, and outpost build-up docking various surface elements (eg. habitat-to-habitat, habitat-to-rover). Chariot and ATHLETE both require communications with the local network and mission operations for command and data handling.

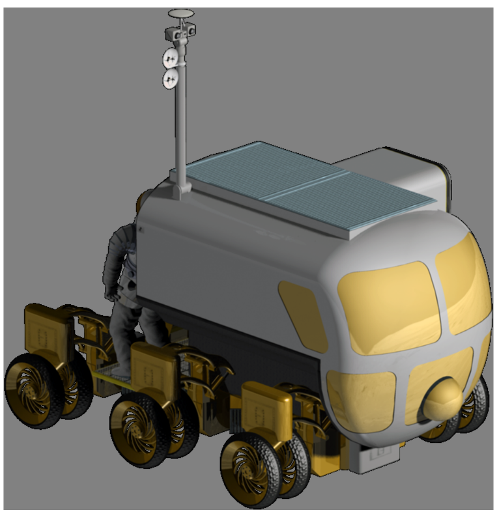
3.2.1 Chariot

The Chariot is a six-wheeled surface vehicle being developed for the lunar outpost[10]. The vehicle utlizes active suspension providing the capability to dynamically level the vehicle deck when on an inclination. As stated above, the vehicle is modular and also reconfigurable as illustrated in figures 4 and 5. In the first figure, the Chariot is configured for unpressurized, EVA crew operation via a control interface in the turret. In figure 4, a prototype is shown with a suited crewman testing the chariot at the Johnson Space Center (JSC) “rock yard.” In figure 5, the chassis for the Chariot has been configured (i.e. loaded) with pressurized crew cabin referred to as the Small Pressurized Rover (SPR) supporting pressurized shirtsleeve environment for surface exploration. Both configurations benefit from RC. The chassis provides mobility and control where reconfigurable assets can be used to implement SHM and control functions for power and wheel systems[11]. Onboard cameras provide navigation, situational awareness, and telepresence capabilities via processing from RC resources. The SPR serves as living quartes and mobile operations center requiring displays for video and tele-operation of other surface elements, SHM, and communications with mission operation either on Earth, the lander, or back at the outpost and each of these benefit from use of RC as previously described.

3.2.2 ATHLETE

As shown in figure 6, the ATHLETE[12, 13] is a six-legged vehicle for lunar surface operations. In the figure, the ATHLETE is demonstrating the self-leveling functionality of the independently controlled legs. It has active suspension and the wheel-on-leg feature enables both walking and rolling, which ever is more efficient based on the terrain. Each leg hosts stereo cameras for autonomous or tele-operation as well as hazard avoidance, exploration, robotic operations, and operator supervision. The wheel forks have tool fixtures to support extending the capabilities of the leg through the attachment of drills or manipulaters for example. The current prototype has PowerPC based Single Board Computers (SBCs) in CompactPCI chassis controlling each leg, six total. Utilizing

Figure 4: Testing of Chariot prototype at JSC



(a) CAD drawing of the SPR

(b) Prototype mockup of the SPR at JSC

Figure 5: SPR being developed for Lunar Surface Systems (LSS)

RC resources, the SBC functionality could be replaced by a single chip considerably reducing power and mass and simplifying the design to one board design to facilitate all of the required processing and control functions. Other possible applications for RC include communications, image processing, hazard avoidance, visual odometry, motor control, and interface management.

Figure 6: Testing of ATHLETE prototype being developed at Jet Propulsion Lab (JPL)

3.3 Habitation

The habitats are among the largest of the surface elements and serve as both living quarters and base of operations for the outpost. A conceptual illustration of the habitat is shown in figure 7. In this picture, multiple habitat elements are connected to build up a larger pressurized living environment for outpost operations, mission planning, and science work. Of all the surface elements, the habitat may have the potential for the greatest use of RC resources. As the operations base for surface activities and a central communications center for earth based mission control, all of the advantages and capabilities provided by RC in communications systems will be utilized in the habitat. Tele-operation of either Chariot or ATHLETE will be managed by video processed in a VPU and locally displayed for real-time situational awareness of the operator. Video streams will be enhanced with artificial illumination and hazard highlighting to ensure safe successful operation of the remote robotic vehicle. Lunar surface science payloads will transmit collected data to the habitat for local archival and processing prior to compression and transmission to eager scientists back on Earth. During crew rotation, the crew will board the SPR, docked to the habitat, which will deliver the crew to the lander for the voyage home. All of these activities utilize RC to achieve their objectives.

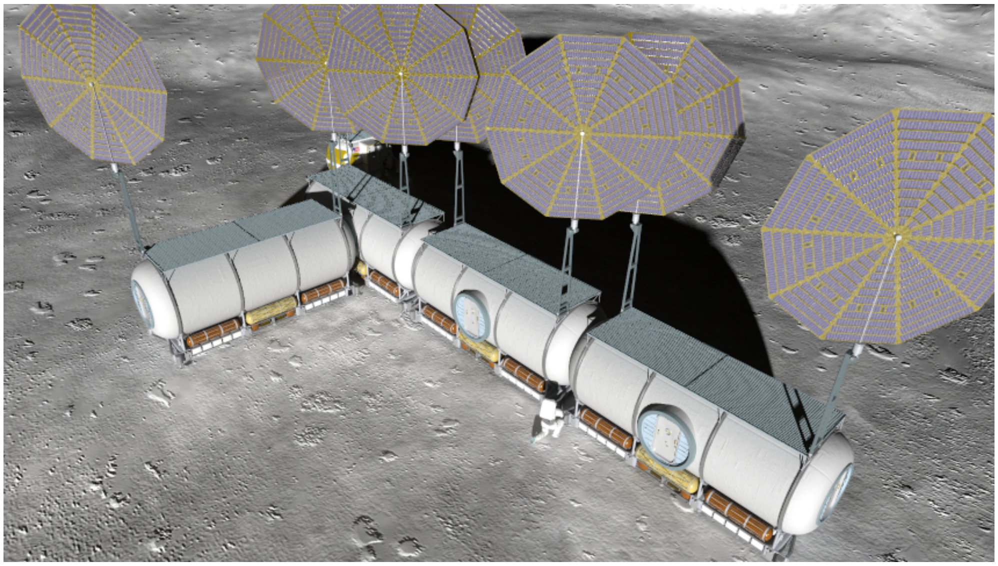


Figure 7: Outpost habitation element illustration

4 Reconfigurable Computing Assets Management

Similar to software libraries, RC provides opportunities for context driven functionality (*programming the reconfigurable element*). While use of RC enables greater flexibility within the given resources, such reconfigurability mandates a capacity to manage the use and configuration of the resources in a safe, verifiable, and traceable manner. As an example scenario, crew tele-operating a chariot to deploy a science package may utilize distributed RC as a network datapath enabling the operation. At the Chariot, RC resources will facilitate image fusion, encoding, compression, and transmission to the habitat. At the habitat, RC will conversely receive the encoded video stream and augment with synthetic highlighting and illumination for display to the crew. This fairly simple example requires mechanisms for discovery or determination of available RC assets both at the Chariot and local to the habitat. Also, suitable application images not only need to be located but must also be deployed to the selected assets along the datapath. Consideration must be given to the various software interfaces including the PLD image management processes; verification of correct deployment (correct image loaded to the RC hardware); as well as the interfaces to the applications. Current concepts build on a *publish-and-subscribe* architecture for resource discovery to enable identification of RC capabilities and properties while access to the images is managed through central network attached storage. To this end, operations concepts are being developed that capture data management plans as well as the software ramification of managing distributed RC hardware and RC application images.

5 Conclusions and Forward Work

The last decade in digital systems development has demonstrated that Reconfigurable Computing will significantly expand our capabilities and enable us to re-evaluate how we design systems. For the lunar surface architecture, the myriad of potential applications increases with further studies. Leveraging experience gained from commercial applications driven by performance and flexibility, the lunar architecture will reap a benefit of reduced power and mass as well as simplify maintenance through interoperable (common) reconfigurable hardware. Each of the elements will embued with the flexibility to retask assets as the missions progress and evolve. A system that may initially be used for video processing for crew display during landing could later be used for navigation or science data processing. While RC alone does not provide all of this functionality, in conjunction with strategic application of industry standards, these could readily yield the evolvability to deploy a system that ten years later realizes new potential and purpose.

Though the project has made great progress in developing preliminary architectural concepts, there are still great opportunities for forward work. Fundamentally, evaluation of the lunar surface architecture will continue seeking opportunities to utilize RC hardware to extend the capabilities of the mission resources without incurring power and mass penalties. For those systems that are currently being prototyped, such as NFIR and ALHAT, the high performace algorithms will be evaluated for porting to PLDs. ALHAT has yet to select the front-end imaging technology and the various stages of processing will be partitioned to optimize performance, power, and flexibility. For those systems still in their conceptual phase, further studies will seek to quantify the benefits of common or standardized RC hardware in terms of maintenance, supportability, performance, and cost (mass and power). This in turn will enable the definition of an optimal RC design optimized for general application across the lunar architecture. Also, as mentioned above in section 4, work needs to be done to establish infrastructure to discover and utilize the RC resources distributed throughout the outpost in a safe and controlled manner.

NASA is working to develop a long term mission to establish an outpost on the lunar surface. On going work to capture the required functionality has indicated various oppportunities for RC to enhance and extend the capabilities of the outpost data management and processing infrastructure. Presented above are examples of applications in RC including navigation, image processing, embedded control, systems health monitoring, and communications. Also presented are several surface elements requiring these applications to perform various objectives in establishing an outpost and exploring the lunar surface. Finally this report closes with a few comments on forward work and a short summary.

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